Transmission-Reflection Method to Estimate Permittivity of Polymer

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Abstract—In transmission-reflection method, the microstrip transmission line coated with an organic polymer as an overlay is used to estimate the permittivity of the polymer film. Scattering parameter response of the microstrip line varies as the permittivity of the overlay or its thickness changes. The permittivity is estimated by minimizing the difference between the theoretical (computed from the analysis of the structure using IE3D simulation tool) and measured scattering parameters.

Keywords—IE3D, microstrip transmission line, organic polymer, permittivity, scattering parameter.

I. INTRODUCTION

Polymers can be processed from solution into thin and flexible films by using spin coating or printing techniques, which is a key factor in manufacturing flexible electronic devices at low cost. Organic polymers have applications in printed electronics operating in the lower end of the RF spectrum. Considerable effort is being focused on extending the frequency of operation of organic polymers. The development of electronic circuits working at high frequencies requires accurate knowledge of electromagnetic properties of materials such as permittivity.

Weir [1] presented an approach to directly determine the dielectric properties from the measurement of the scattering parameters, when a sample of material is inserted in a waveguide. As the device cross section must be filled with the sample in this method, so limits its application. Barry [2] used a strip transmission line device loaded with the unknown material and scattering parameter measurements were made using network analyzer. In order to compute \( \varepsilon_r \) and \( \mu_r \) correctly, the scattering parameters of the empty and loaded test device were measured with a network analyzer. During the scattering parameter measurements and resulting calculations, the mismatch at the stripline-to-coax joint and impedance differences between the stripline and the network analyzer dominated. Abdulnour et. al. [3] proposed a generic approach to accurately measure microwave and millimeter wave properties of dielectric materials, i.e. to determine the complex permittivity of dielectric materials based on a microstrip transmission line measurement.

They determined the scattering parameters of a discontinuity embedded in a microstrip line with a network analyzer using TRL calibration procedure and the samples used were in the form of rods. This technique is more useful for the measurement of bulk properties of liquids. However, it may not be easy to extend this method for polymer film characterization.

Hinjosa et. al. [4] presented a measurement method for the determination of the complex permittivity and permeability of film shaped materials. \( \varepsilon_r \) and \( \mu_r \) were computed from scattering parameter measurements of microstrip lines with substrate as the material under test. This method requires the complicated procedure of sample fabrication and works well only when the transition effect of coax-to-microstrip is small, means the approximate substrate permittivity should be known before the measurement so that the cell can be designed to have a characteristic impedance of 50\( \Omega \). Lee et. al. [5] proposed two-microstrip line method for the measurement of the dielectric constants of substrates. According to them, dielectric property of material can be estimated if it is the substrate of a microstrip line, which is not easy, as it is difficult to deposit the metal tracks on polymer, as in our case.

Queffelec et. al. [6] in 1994 presented a method for determining the complex permittivity and permeability using reflection-transmission measurement of the scattering parameters of a microstrip test device. In this method, the sample under test was laid on the microstrip substrate close to the central conductor to obtain the strong interaction between the wave and the sample under test. As characterization of materials, requires the knowledge of both reflection and transmission coefficients with the sample under test, so the processing of the data from the scattering parameter measurements, calls for a rigorous electromagnetic analysis of the test device (direct problem) together with an optimization program (inverse problem).

Microstrip transmission line shows many properties which makes it suitable as a medium for measurement of complex dielectric permittivity. The effective permittivity of a microstrip transmission line is dependent on the permittivity of the region above the line too.
This effect can be utilized in implementing microwave circuits to estimate the dielectric permittivity and such a system could be based on determining the effective permittivity of a microstrip line covered by an unknown dielectric substance. To estimate the permittivity of organic polymers at microwave frequency, the microstrip transmission line structure is used.

The material to be characterized can be used as a substrate (Figure 1) or an overlay (i.e. superstrate) (Figure 2) for a microstrip transmission line. It is convenient to deposit the overlay than fabricating microstrip transmission line using organic polymer as the substrate. As the field passing through the overlay is much smaller compared to that passing through the substrate (Figure 3), the scattering parameters are less sensitive to the change in the properties of the overlay.

In this paper, a technique has been presented to characterize the dielectric properties of an organic polymer film using the two-port scattering parameter matrix of a microstrip transmission line. The two-port scattering parameter matrix is a function of dimensions of the transmission line and the electrical properties of the substrate. Given the dimensions of the transmission line and the substrate properties, it is possible to uniquely determine the scattering parameters of the transmission line. However, the converse is not necessarily true. For example, if the scattering parameters of a transmission line are known, it is not obvious to determine the dielectric properties of the substrate material and dimensions of the transmission line.

Zeland IE3D simulation tool based on MoM (Method of Moments) is used to compute the scattering parameters of a finite length microstrip transmission line covered with an organic polymer overlay. We show that the scattering parameters depend on the permittivity of the overlay. An optimization based technique is used to demonstrate the possibility of determining the dielectric properties of the polymer film from the two-port scattering parameter matrix. Finally, the paper concludes with a discussion on the accuracy of the method.
II. ANALYSIS OF MICROSTRIP TRANSMISSION LINE WITH AN OVERLAY

The parameters of the microstrip transmission line are listed in Table 1. Microstrip transmission line design formulae are used to compute the width of the line and the effective permittivity. We find that to obtain a characteristic impedance of 50Ω, the line has to be 2.439mm wide (w=2.439mm). The effective permittivity of the microstrip line is 1.857.

We now model the structure using Zeland IE3D simulation tool, and compute the two-port scattering parameters. Choosing 20 cells per wavelength gives converged solution. We have used 5GHz as the reference frequency for meshing.

Table 1
Microstrip Transmission Line Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate size</td>
<td></td>
<td>60mm x 45mm</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>ε_r</td>
<td>2.18</td>
</tr>
<tr>
<td>of the substrate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width of line</td>
<td>w</td>
<td></td>
</tr>
<tr>
<td>Height of substrate</td>
<td>h</td>
<td>0.787mm (=31mils)</td>
</tr>
<tr>
<td>Thickness of copper strip</td>
<td>t</td>
<td>35µm</td>
</tr>
<tr>
<td>Copper conductivity</td>
<td>σ</td>
<td>5.183 x 10^7 S/m</td>
</tr>
<tr>
<td>Loss tangent</td>
<td>tanδ</td>
<td>0.0313</td>
</tr>
</tbody>
</table>

The scattering parameters of a microstrip transmission line for different line widths (w=2.439mm, 2.61mm, 2.63mm, 2.65mm) are shown in Figure 4 to Figure 7. Using w=2.439mm (computed using design formulae) we get the |S_{11}| of -25dB. By adjusting the width of the line slightly, it is possible to reduce the mismatch to -45dB. We have chosen w=2.63mm as the width of the transmission line for further analysis. The ripple in the |S_{12}| is also considerably reduced by choosing w=2.63mm rather than the design value of 2.439mm as shown in Figure 6.

We now introduce an overlay on the microstrip transmission line. The analysis have been performed for different values of overlay thickness (d=1µm, 5µm, 10µm, 20µm, 30µm and 35µm) and relative permittivity (κ=1, 2, 3, 4, 6, 8). Scattering parameters response corresponding to κ=4 is shown in Figure 8 to Figure 11, which is obtained when thickness of the overlay d is changed (d=1µm, 5µm, 10µm, 20µm, 30µm and 35µm), while keeping the relative permittivity of the overlay constant (κ=4).

Figure 12 to Figure 15 show the effect of changing κ for fixed value of d (=35µm) on the terminal scattering parameters. Form Figure 8, we can conclude that, as the thickness of the overlay increases, |S_{11}| degrades monotonically. Similarly, in Figure 12 we observe that |S_{11}| degrades as κ increases (κ=1, 2, 3, 4, 6, 8), when thickness of the overlay is 35µm. However the change in the properties of the overlay does not affect the |S_{12}| appreciably as shown in Figure 10 and Figure 14.

Thus, the permittivity of the overlay has an observable influence on the reflection coefficient. The monotonic nature of change in |S_{11}| with κ suggests that given |S_{11}| versus frequency, it is possible to estimate the permittivity, κ. Of course, it is assumed that the thickness of the overlay is known.
Figure 6 Magnitude of transmission coefficient of a microstrip transmission line showing the effect of width.

Figure 7 Phase of transmission coefficient of a microstrip transmission line showing the effect of width.

Figure 8 Magnitude of reflection coefficient of a microstrip transmission line with overlay (κ=4) showing the effect of thickness.

Figure 9 Phase of reflection coefficient of a microstrip transmission line with overlay (κ=4) showing the effect of thickness.

Figure 10 Magnitude of transmission coefficient of a microstrip transmission line with overlay (κ=4) showing the effect of thickness.

Figure 11 Phase of transmission coefficient of a microstrip transmission line with overlay (κ=4) showing the effect of thickness.
III. ESTIMATION OF PERMITTIVITY

In this section, we present an optimization based technique to compute \( \kappa \) (permittivity of the overlay) from the scattering parameters of the structure. The permittivity of the overlay can be determined by matching the simulated and measured scattering parameters using numerical optimization technique.

The optimization problem involves minimizing an objective function, which is the difference between the simulated and measured scattering parameters. The objective function can be expressed as sum of the squared function as given by Eq. (1) [7].

\[
\text{Total error} = E(X) = \sum_{f} \sum_{i} \sum_{j} \left| \frac{S_{ij}(X)}{S_{ij}} \right|_{\text{theoretical}} - \left| \frac{S_{ij}(f)}{S_{ij}} \right|_{\text{measured}}^2
\]

Where in \( X = (f, \varepsilon', \varepsilon'', \mu', \mu'') \), \( f \) is frequency, \( \varepsilon = \varepsilon_0 \varepsilon_r = \varepsilon_0 (\varepsilon' - j\varepsilon'') \) is complex permittivity, \( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \) is the permittivity of free space, \( \varepsilon_r \) is relative complex permittivity, \( \varepsilon' \) is the real part of relative complex permittivity, \( \varepsilon'' \) is the imaginary part of relative complex permittivity and \( \mu = \mu_0 \mu_r = \mu_0 (\mu' - j \mu'') \) is complex permeability, \( \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \) is the permeability of free space, \( \mu_r \) is relative complex permeability, \( \mu' \) is the real part of relative complex permeability, \( \mu'' \) is the imaginary part of relative complex permeability.
Though the proposed method is general, we use it to compute only the real part of the relative complex permittivity (\(\varepsilon'\)) of the overlay. Nelder-Mead optimization algorithm [8] is combined with IE3D, and an integrated code is developed in MATLAB to estimate the permittivity of the overlay.

The measured scattering parameters (\(S_{\text{measured}}\)) are obtained from the simulated scattering parameters (\(S_{\text{theoretical}}\)) by introducing fixed amount of error both in the magnitude and phase. MATLAB m-file, measedit.m is used to edit the measured.sp file for scattering parameters and spaspar.m m-file generates the measured scattering parameters by introducing an error in both the amplitude and phase of simulated scattering parameters. To generate the measured scattering parameters for a particular starting value of \(\kappa\), corresponding simulated scattering parameters are used as the base, and its amplitude and phase both are multiplied with an error function, which is a modified random function of the form \((1+ (\text{rand}(81, 8)-0.5))\times 10\). Eight corresponds to scattering parameter terms and 81 is the number of frequency points in the frequency range 1-5GHz, therefore in the error function rand (81, 8) is used which gives a random matrix of the size (81, 8) with its elements lying between 0 and 1.

We now have measured scattering parameters file, which enlists complex scattering parameter matrices as a function of frequency. This forms one of the inputs to the optimization program. Another input to the optimization program is the starting value of \(\kappa\). With these two inputs, the optimizer calls a function which computes the error between the measured scattering parameters (\(S_{\text{measured}}\)) and the simulated scattering parameters (\(S_{\text{theoretical}}\)) for a specified value of \(\kappa\).

The flowchart of the function (final.m) used by the optimizer is shown in Figure 16. Numerical optimization function starts with an appropriate initial value for \(\kappa\). The first step is to check, if \(\kappa\) value input to the function is greater than or equal to 1. If not, the function returns a high value of error (\(E(X) = 10^5\)), thus excluding \(\kappa<1\) from the search space.

When \(\kappa\geq 1\), editgeo.m m-file is invoked to modify the .geo file to save the current value of \(\kappa\). In IE3D, the geometry information of the structure is stored in the .geo file, which is an XML file. The next step is to run the .sim by using IE3DOS, so runie3d.m m-file is called. The .sim file is generated by simulating the .geo file manually using IE3D and this .sim file is used during optimization. The simulation input data like the frequency points and other control parameters are saved in the .sim file. IE3D is called using the .sim file as the command line argument.

The .sim file tells IE3D where to find the .geo file, which frequency points a simulation should use, and where to the save the output files. To perform an IE3D simulation, we need both the .sim file and the .geo file.

Next, spedit.m m-file is called to edit the .sp file to obtain the theoretical scattering parameters. objective_f.m m-file, calculates the total error \(E(X)\), which is obtained from the sum of the squares of the individual error terms, the difference between theoretical and measured scattering parameters over the frequency range as given by Eq. (1).

The error value is returned to the optimizer fmin.m m-file, depending upon the error value the optimizer generates a new value of \(\kappa\), and the whole process is repeated until the change in the value of \(E(X)\) is less than \(10^{-5}\) between two iterations. The optimizer uses Nelder-Mead algorithm function fminsearch of MATLAB for optimization [9].

The flowchart of the function used by the optimization program is shown in Figure 16.

![Flow chart](image-url)

**Figure 16** Flow chart of the function used by the optimization program.

IV. RESULTS AND DISCUSSION

Figure 17 shows the variation of actual value of \(\kappa\) with optimized value of \(\kappa\), when there is an error in both the amplitude and phase of measured scattering parameters. As the relative error in the optimized value of \(\kappa\) is the ratio of the difference between the actual value of \(\kappa\) and optimized value of \(\kappa\) to the actual value of \(\kappa\).
Figure 18 shows how relative (%) error in optimized value of $\kappa$ varies with actual value of $\kappa$ when an error exists in both the amplitude and phase of measured scattering parameters.

All optimizations terminated successfully, when the change in $\kappa$ satisfies the termination criteria of $10^{-4}$ and $E(X)$ satisfies the convergence criteria of $10^{-4}$.

Then scattering parameters of a finite length microstrip transmission line covered with an organic polymer overlay are obtained, which depend on the permittivity of the overlay. We observe that $|S_{11}|$ degrades as $\kappa$ increases, when thickness of the overlay is $35\mu$m. Also $|S_{11}|$ degrades monotonically as the thickness of the overlay increases.

An optimization based technique is used to demonstrate the possibility of determining the dielectric properties from the two-port scattering parameter matrix. The optimized value of $\kappa$ is approximately same as the actual value of $\kappa$, when there is an error in the amplitude and phase of measured scattering parameters used for optimization.

**REFERENCES**


